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Using Wireless Vibration Monitoring to Enable Condition-Based Maintenance of Rotating Machinery in the Water and Wastewater Industries

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Abstract

While sensors traditionally have required the use of wires, their wireless counterparts have become increasingly popular since the ratification of the WirelessHART and ISA100.11a specifications. Within water and wastewater, it is expected that these wireless technologies might find first use within asset monitoring, paving the way for the implementation of condition-based monitoring schemes. In this paper, we will introduce condition-based maintenance and wireless instrumentation, including high-level requirements and operational drivers for using this technology in condition-based maintenance. We will also present a pilot installation on wireless vibration monitoring of several pumps in a water pumping station in Oslo, Norway.

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Keywords: Wireless Sensor Networks; Wireless Instrumentation; Condition-Based Maintenance; Real-time Monitoring; Asset Management

1. Introduction

In industrial maintenance operations, the objective is to restore an asset to a state in which it can perform its required function. Historically, asset management has been performed according to reactive (run-to-failure) models, but lately there has been a shift towards planned and proactive maintenance. If successfully implemented, introducing proactive

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maintenance schemes can be expected to give several benefits over traditional maintenance models. For instance, vibration monitoring of water pumps in combination with condition-based maintenance is reported to provide a substantial reduction in maintenance costs as well as in the number of bearing and motor faults [1].

On the sensor side, wireless instrumentation has become increasingly popular in the process industries since the ratifications of the WirelessHART and ISA100.11a specifications, as described by Kim et al. [2] and Petersen et al. [3] respectively. Being defined as the merger of wireless sensor network technologies and field instruments, this technology offers a cost-efficient and flexible alternative to traditional wired field instrumentation. It is expected that the first applications of wireless instrumentation within the water and wastewater industries will be found within the fields of safety detection systems and asset monitoring [4], and the case presented in this paper falls into the latter.

The background for this paper has been the question of *whether wireless vibration monitoring can be used to enable condition-based maintenance of rotating machinery in the water and wastewater industries.* In order to answer this question, a wireless vibration monitoring solution has been deployed on several pumps in an operational water pumping station in Oslo, Norway. The data from this pilot installation has then been processed by experts in vibration monitoring, before being presented to Oslo Water and Sewerage Works.

In the paper, we will first give a short introduction to condition-based maintenance, before presenting drivers and requirements for using this methodology for maintenance of rotating machinery. We will then provide some information on wireless instrumentation, before presenting the details of the aforementioned pilot installation of vibration monitoring equipment. Finally, the conclusions from our work is presented, including some thoughts on what could be the next steps regarding research on CBM within the water and wastewater industries.

2. Condition-based maintenance

In industrial maintenance operations the objective is to restore an asset to a state in which it can perform its required function. Historically, asset management has been performed according to reactive (run-to-failure) models, but lately there has been a shift towards proactive maintenance where faults are corrected before they result in a machine failure. This shift is driven by a motivation for optimizing the assets' reliability while at the same time reducing the corresponding maintenance costs. However, finding the ideal time for performing maintenance (that is, neither too often nor too late) is not trivial, and it can be relevant to divide proactive maintenance into the two categories *planned* and *condition-based* depending on how the decisions are made. In *planned maintenance* the frequency of maintenance operations are based on recommendations from the equipment manufacturer in combination with internal practices. The disadvantage of this scheme is that there are large deviations in the deterioration of seemingly identical equipment. Furthermore, the maintenance actions themselves will only to a varying degree restore the health of an asset to "as good as new" [5]. This means that a maintenance operator will have to accept either an increased risk of failure or that the maintenance activities at best may be useless, and at worst will introduce new faults. In *condition-based maintenance* (CBM) the maintenance actions are based on the equipment's actual condition, as collected through sensors that monitor relevant equipment state parameters, and logged event data related to the physical asset [6]. In this context, event data includes both what has happened to the asset (e.g. installation, break-downs, overhauls) as well as any actions that have been performed on the asset (e.g. repairs, maintenance, oil change). This enables a more relevant foundation for maintenance decisions, as the maintenance operators may have indications of faults before they result in a failure, and also positive confirmation when everything is running as it should. Although CBM comes at an extra cost by requiring both extra instrumentation and knowledge on data interpretation, it is regarded a better choice than conventional maintenance schemes in cases where both maintenance and failure are costly [6].

As described by Jardine et al. [6] a CBM program consists of the following three key steps:

1. **Data acquisition** – to obtain relevant system health parameters
2. **Data processing** – to analyze and interpret the data collected in step 1 for better understanding
3. **Maintenance decision-making** – to recommend efficient maintenance policies based on the processed data from step 2

In the *data acquisition* step, both condition data from sensors and event data from operators related to the targeted physical asset are collected. Examples of condition data may be lubricant pressure, temperature or vibration.

In the *data processing* step the data is first manually checked for consistency and potential errors, and then subjected to further analysis. This step requires in-depth knowledge on both the data acquisition process and on the mechanical properties of the asset.

Finally, in the *maintenance decision-making* step, the information from the previous steps is used to plan future maintenance activities. This may involve prognostic tools for predicting how much time is left before a failure occurs.

Note that while traditional maintenance operations normally will be planned by the operators themselves, CBM will in general require some sort of expert teams providing input to the maintenance planners. These teams might be either internal (typically for larger companies) or outsourced to service providers (typically for smaller companies) [7].

3. Drivers and requirements for condition-based maintenance of rotating machinery

Maintenance in general is performed to increase the reliability, utilization, performance and life-time of the assets in question. On the other side, the maintenance operations should come at the lowest possible cost; or more general, the *total cost per unit time* (also known as *life-cycle costs*) should be as low as possible [6]. All these factors will (or should) normally constitute the main drivers for any maintenance operations.

The high-level drivers for maintenance can further be decomposed into more detailed motivational factors for a specific facility or set of assets. These will in turn depend on a facility's location, its criticality and its tolerance against single failures. Furthermore, specific gains or benefits may be both domain specific (e.g. energy, water, oil and gas) and related to specific facilities within each domain. This means that generic considerations for CBM may not be feasible for all facilities in water and wastewater. It also means that identifying and evaluating the possible benefits of introducing a CBM scheme is challenging, especially in organizations which adhere to traditional maintenance schemes (run-to-failure or planned) and where the potential benefits and costs of CBM are distributed among multiple organizational units.

Although the process of identifying viable business-cases is outside the scope of this paper, it is nevertheless important to reduce the financial and operational load when trying out CBM solutions, as is the case for piloting of any new technology. The following aspects and high-level requirements may be considered relevant when planning for the introduction or piloting of CBM:

- The capital and operational expenditures (CAPEX and OPEX) regarding the CBM system (including sensors) should be as low as possible.
- There should be minimal maintenance of the CBM system.
- Existing infrastructure (for instance communication link between the facility and operation center) should be used when possible.
- The CBM system should be easily integrated with existing monitoring and control systems.

Note that the issues above are mainly related to the *data acquisition* step and how this step can be carried out with as little effort as possible. Properly addressing these issues will let the organization focus on the two last steps of a CBM program, namely *data processing* and *maintenance decision-making*, which are where the real challenges lie in terms of how to understand condition data and on how to implement the optimal decision processes.

4. Wireless instrumentation for condition monitoring

To enable the collection of relevant condition-related parameters for the *data acquisition* phase of CBM, it is necessary to deploy sensors on the monitored machinery. Since the CAPEX, OPEX and maintenance cost of the CBM system should be as low as possible, finding a cost-efficient solution for sensors and local communication is imperative. One such solution can be found in wireless instrumentation, which is defined as the merger of wireless sensor network technologies and process automation disciplines [8]. A wireless field instrument is typically a traditional, formerly wired, sensor or actuator equipped with an additional radio transmitter, antenna and power supply (battery). The instrument parts (i.e. sensor or actuator elements) are the same as for a wired instrument, and they have the same measurement performance characteristics and accuracies. Wireless instrumentation has become increasingly popular in the process industries since the recent emergence of the WirelessHART and ISA100.11a specifications, as described in further detail by Petersen et al. [3]. As both standards provide self-healing and self-configuring multi-hop mesh networking, wireless networks based on WirelessHART and ISA100.11a are fully capable of providing robust and reliable communication in the harsh environments typically encountered in process plants and other industrial facilities [8].

The main motivational and financial driver for deploying wireless instrumentation can be found in modification projects on existing facilities [8], mainly due to the reduced installation costs and improved flexibility and scalability enabled by having instruments without wires. With features such as these, it is natural to assume that wireless instrumentation should be well suited for CBM within the water and wastewater sector [4].

5. Pilot installation

In this paper, we have defined the research question as to *whether wireless vibration monitoring can be used to enable condition-based maintenance of rotating machinery in the water and wastewater industries***.** This rather broad scope has then been deliberately narrowed down by focusing on one particular type of facility and one specific technology for wireless vibration monitoring. As this is a case study, a failure in confirming the research question will therefore not automatically invalidate the hypothesis. Vice versa, any identified benefits in this one case do not necessarily transfer to other cases. Still, the experiences from a specific case should provide useful insight into the process of both acquiring relevant data and presenting this data as condition information, which are the goals of the first two key elements of a CBM program as presented in section 2.

5.1. Facility description

In cooperation with Oslo Water and Sewerage works a medium-sized water pumping station was selected as the location for the pilot installation. The pumping station consists of four parallel water pumps (see **Errore. L'origine riferimento non è stata trovata.**), located in the basement of the facility. During normal conditions only one or two of the pumps are in operation. Four electric motors, one for each pump, are located on the ground floor.

5.2. Pilot setup

In order to monitor the condition of the rotating machinery at the facility, the motors and pumps were equipped with wireless vibration sensors. The sensors, three for each motor and one for each pump, were of the type WiMon 100 from ABB. The sensors communicate wirelessly by using the WirelessHART standard, enabling installation and battery-supported operation without the use of wires. A WirelessHART gateway from Pepperl+Fuchs was deployed in the ground floor of the facility, enabling wireless communication with all the WiMon 100 sensors. The WirelessHART gateway also had a wired Ethernet connection to an on-site laptop running the *WiMon Data Manager* for network configuration, data acquisition and data analysis. The on-site laptop was remote-controlled by ABB over the Internet.

For an illustration of the system architecture, see Fig. 2. As an example, this figure also shows how the sensors related to motor 4 and pump 4 communicate with the gateway. As mentioned in section 4, WirelessHART provides multi-hop communication when direct links do not provide sufficient quality. Such a multi-hop route can be observed at the sensor on pump 4, which uses one of the sensors on motor 4 as a relay for transmitting data to the gateway. This routing is handled automatically by the gateway throughout the entire lifetime of the network, and is dynamically updated according to temporary or permanent link quality variations due to noise, interference and/or fading. Similar routing paths are employed by the sensors on motors and pumps 1-3, although not illustrated in the figure.

Fig. 1. Water pumping station in Oslo, Norway (with four pumps)

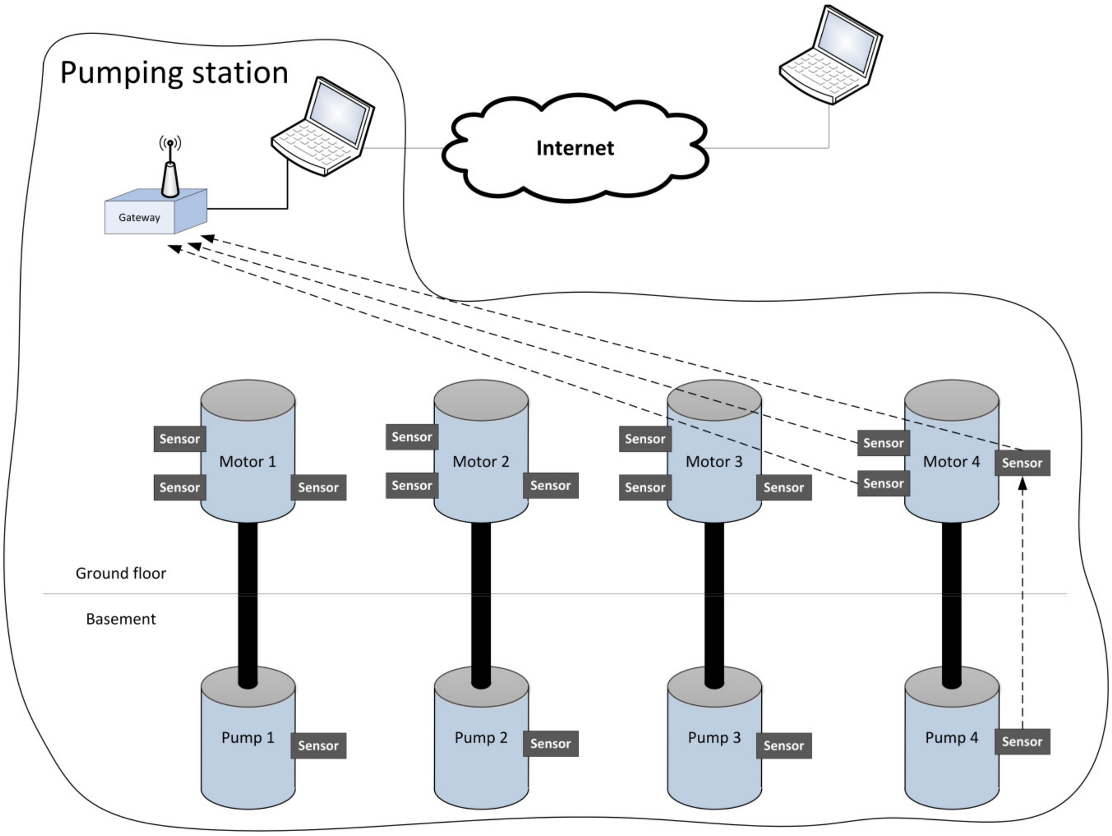

Fig. 2. System architecture (including communication links from sensors on motor 4 and pump 4, for illustrative purposes)

5.3. Data acquisition, analysis and results

The vibration data was collected over a three-month period, and subsequently analyzed by ABB. The results were then presented to Oslo Water and Sewerage Works in order to see if the vibration data had the potential of providing relevant information with regard to when maintenance should be performed.

An example of the findings is presented in Fig. 3a, where the frequency spectrum of the vibration measurements from motor 2 is shown. Here, there are clear repetitive energy spikes at 3.09 x RPM (revolutions per minute). Consulting the technical sheet for the bearing in question (Fig. b) reveals that this frequency conforms to the "*over-rolling frequency of one point on the outer ring*". This indicates that there is a fault in the outer ring of the bearing in motor 2, which at some point in the future will result in a bearing breakdown. Note however that one single measurement cannot tell *when* the bearing will break; it can only indicate the existence of the fault.

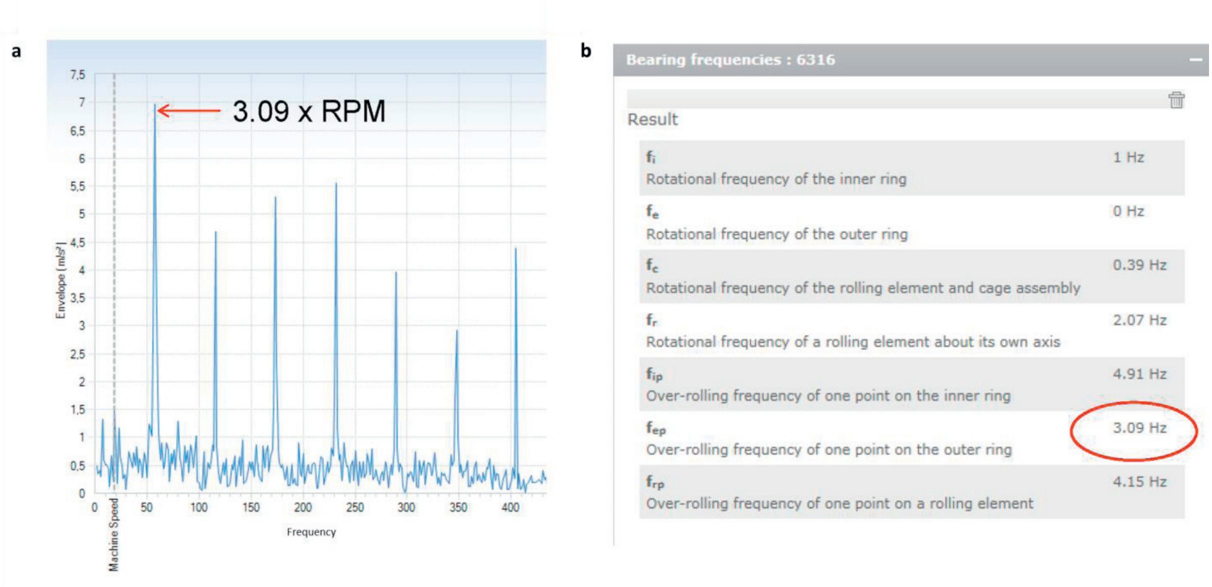

Fig. 3. (a) Vibration measurements (envelope) for Motor 2; (b) Bearing frequencies for Motor 2 (Courtesy of ABB / WiMon Condition Monitoring System).

5.4. Maintenance decision-making

While the vibration data indicates a fault in the bearing of one motor, it still remains to decide how this information should influence the maintenance plan. The results from motor 2 indicate (most probably) no immediate threat of failure, only that there is a developing fault in the bearing. This fact is simultaneously both very definite and very fuzzy; there is without doubt something wrong, but the data cannot tell how serious this fault is. For an organization that has implemented a CBM strategy, this information can be used as a trigger for further investigation, perhaps as simple as performing more frequent follow-ups of the future wireless vibration measurements from this asset. However, for an organization that still follows traditional maintenance strategies, such fuzzy and time-limited (or perhaps also historic, as in our case) condition information might on the contrary lead to uncertainty on what to do. This leads to the observation that CBM is not mainly a question of having the optimal monitoring technology, but rather a question of how to handle both historic and future condition data from an organizational point-of-view. These reflections also coincide with [9], where the organizational aspects are reported to constitute the main threats against a full-scale implementation of CBM.

6. Conclusions

The presented pilot on wireless vibration monitoring has showed that wireless monitoring technologies can provide early fault detection, which in turn should have the potential of being used to optimize maintenance planning and reduce probability of failure. From a technical point-of-view, the pilot installation at a pumping station in Oslo proves that wireless vibration sensors are fully capable of enabling the data acquisition step of a CBM regime. The wireless network performed adequately, and as could be seen from the frequency spectrum of Motor 2 (Fig. a), the vibration measurements were able to detect a fault in one of the bearings. As such, the pilot installation can be considered a success. However, there are still non-technical challenges that must to be addressed before CBM solutions can be successfully implemented in an organization: how should vibration data be transferred into executable information, how could new condition information be used in strategic and operational decisions, and how should the financial benefits of condition-based maintenance be held up against the actual costs of such a maintenance scheme. These questions remain unanswered at the end of the project, and are to be addressed in subsequent research activities.

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References

[1] Aronen, R., Dierssen, G., Targeted Maintenance in Municipal Water Systems, Pumps & Systems Expo 2004. Baton Rouge, Louisiana, USA.
[2] Kim, A.N., Hekland, F., Petersen, S., Doyle, P., When HART goes wireless: Understanding and implementing the WirelessHART standard, in Proc. IEEE ETFA, 2008, 899-907.
[3] Petersen, S., Carlsen, S., WirelessHART vs. ISA100.11a: The Format War Hits the Factory Floor, IEEE Industrial Electronics Magazine, 5 (2011) 23-34.
[4] Petersen, S., Myhre, B., Røstum, J., Wireless Instrumentation for the Water and Wastewater Industries, in Proc. 12th International Conference on Computing and Control for the Water Industry, CCWI2013. Procedia Engineering 70 (2014) 1314 – 1323.
[5] Heng, A., Zhang, S., Tan, A.C.C., Mathew, J., Rotating machinery prognostics: State of the art, challenges and opportunities, Mechanical Systems and Signal Processing 23 (2009) 724–739.
[6] Jardine A. K. S.,Lin, D.Banjevic, D., A review on machinery diagnostics and prognostics implementing condition-based maintenance, Mechanical Systems and Signal Processing 20 (2006) 1483–1510.
[7] Valland, A., Dyrkoren, E., Heggset, J., Transfer of methods and experiences from operation and maintenance in other industries to offshore wind farms, in Proc. 24th International Conference on Condition Monitoring and Diagnostic Engineering Management, COMADEM (2011).
[8] Petersen, S., Carlsen, S., Wireless Instrumentation in the Oil & Gas Industry - From Monitoring to Control and Safety Applications, SPE Intelligent Energy International 2012, Utrecht, The Netherlands, 1-14.
[9] Bengtsson, M., Jackson, M., Important Aspects to take into Consideration when Deciding to Implement Condition Based Maintenance, in Proc. 17th International Conference on Condition Monitoring and Diagnostic Engineering Management, COMADEM (2004)